

## The Assembly History of Massive Galaxies: What Do We Know?

Christopher J. Conselice

*University of Nottingham, England*

### Abstract.

Understanding the formation history of massive galaxies is one of most popular and longstanding problems in astronomy, with observations and theory addressing how and when these systems assembled. Since the most massive galaxies in today's universe, with  $M_* > 10^{11} M_\odot$ , are nearly all elliptical with uniform old stellar populations, we must probe higher redshifts to discover their full origins. A recent consensus has developed that nearly all  $M_* > 10^{11} M_\odot$  galaxies we see today were established by  $z \sim 1$ , with at most a factor of two growth in stellar mass and number densities at lower redshifts. We review the evidence for this, and discuss how recent observations of star formation rates, colors, and morphologies of massive galaxies at  $z < 1$  with  $M_* > 10^{11} M_\odot$  show that these systems are still experiencing some evolution. Massive galaxies undergo on average a single major merger at  $z < 1.5$ , and roughly half are experiencing star formation at the same redshifts. The highest mass galaxies, with  $M_* > 10^{11.5} M_\odot$ , appear in similar abundance at  $z < 2$ , suggesting that extremely massive galaxies are mostly formed very early in the universe. Observations at  $z > 1.5$  demonstrate that major galaxy mergers are the primary method for assembling these massive galaxies, with nearly all of this merging occurring at  $z > 2$ , with on average 4 to 5 major mergers taking place at  $z = 1.5 - 3$ .

### 1. Introduction

Determining when and how galaxies in the universe formed is one of the most outstanding problems in cosmology and galaxy formation. Galaxies are predicted in Cold Dark Matter based models of structure formation to assemble gradually with time through the merging of smaller systems (e.g., White & Rees 1978). While there is some evidence for this process, at least in terms of galaxies (e.g., Le Fevre et al. 2000; Patton et al. 2002; Conselice et al. 2003a,b; Bridge et al. 2007), many details are still lacking. Alternatively, massive galaxies, which are mostly ellipticals in today's universe (e.g., Conselice 2006a), may have formed in a very rapid collapse of gas (e.g., Larson 1974).

As such, massive galaxies are largely the test-bed for galaxy models. Understanding their evolution observationally is therefore an important test of the physics behind galaxy formation. As star formation and merging activity has been seen in ellipticals from  $z \sim 0$  to  $z \sim 1$  (Stanford et al. 2004; Lin et al. 2004; Teplitz et al. 2006), it is not clear when or how the most massive galaxies finally assembled. If it were possible to date every star in nearby massive galaxies, we could in principle determine the formation epoch and time-scales of these systems by examining their individual stars. We cannot however resolve stars in all but the nearest galaxies, and their integrated stellar properties, such as colors, become degenerate after about 5 Gyrs (e.g., Worthey 1994). Stellar

ages also do not necessarily correlate with the assembly of mass through, for example, merging activity (Conselice 2006b; De Lucia et al. 2006; Trujillo et al. 2006). An alternative approach towards understanding massive galaxies and their evolution is empirically measuring the number densities, morphologies, star formation rates, and the stellar masses of massive systems at some fiducial time, and to compare these to similar quantities at different times (redshifts), and with models.

Observational evidence suggests that passively evolving massive galaxies exist at  $z \sim 1$ , and likely at even early times, at  $z > 2$  (Fontana et al. 2004; Daddi et al. 2004; Glazebrook et al. 2004; Saracco et al. 2005). Recent claims also exist for the establishment of the full massive galaxy population by  $z \sim 1$  (e.g., Drory et al. 2005; Bundy et al. 2005, 2006; Borch et al. 2006; Cimatti et al. 2006). However, what is not yet clear is if number densities measured in these surveys are able to rule out evolution at  $z < 1$  due to uncertainties in measuring stellar masses, number densities, and cosmic variance.

On the other hand, at  $z > 1.5$  it appears that there are significantly fewer massive galaxies than at  $z < 1.5$  (e.g., Fontana et al. 2004). Observationally, a large fraction of the most massive galaxies at  $z > 1.5$  are undergoing major mergers, which are able to construct the stellar masses of these galaxies rapidly (e.g., Conselice 2006b). The merger history at  $z < 1.5$  is not as clear, with observations inconsistent on whether there is evolution in the massive galaxy population at  $z < 1$  (e.g., Bell et al. 2004; Brown et al. 2007; Scarlata et al. 2007). We argue in this review that after taking into account all sources of error, and by examining the physical properties of massive galaxies at  $z < 1.5$ , that at least one major merger is occurring within these systems. A significant fraction of massive galaxies at  $z < 1.4$  also have not yet acquired a smooth elliptical structure, and have ongoing star formation. Thus, while the bulk of the stellar mass in massive galaxies is present by  $z \sim 1 - 1.5$ , there is still observable evolution. Throughout this review we use a standard cosmology of  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 1 - \Omega_\Lambda = 0.3$ , and a Chabrier IMF for stellar mass calculations.

## 2. Number and Mass Densities

The most basic method for understanding the evolution of massive galaxies is measuring how their number densities and integrated mass densities change as a function of time. This is typically done through the use of stellar masses (e.g., Brinchmann & Ellis 2000; Conselice et al. 2005a,b; Bundy et al. 2005, 2006). Alternatively, it has remained popular to determine the number densities for luminous, red, or elliptical galaxies, although these selection methods will produce biases when trying to understand the evolution of massive galaxies, as star formation and morphological evolution are occurring in “early-type” galaxies at  $z \sim 1$  (e.g., Stanford et al. 2004; Teplitz et al. 2006). Recent work on measuring densities suggests that within the uncertainties galaxies with large stellar masses, with  $M_* > 10^{11} M_\odot$ , are largely in place at  $z \sim 1$  (Glazebrook et al. 2004; Bundy et al. 2005, 2006; Cimatti et al. 2006).

Figure 1 shows an updated version of how the number and mass densities of galaxies with stellar masses  $M_* > 10^{11.5} M_\odot$  and  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$  evolve out to  $z \sim 2$ , as seen in the large  $1.5 \text{ deg}^2$  Palomar Observatory Wide-

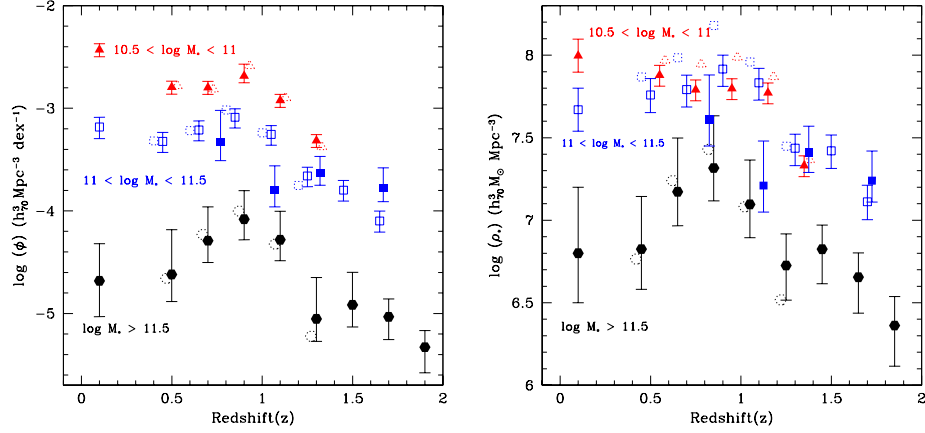


Figure 1. Left panel: the evolution in the number densities for galaxies of various stellar masses between  $z \sim 0.4 - 1.4$ . Right panel: the stellar mass density evolution as a function of stellar mass at the same redshift intervals. The points at  $z \sim 0$  are taken from Cole et al. (2001). The error bars listed on both the numbers and stellar mass densities reflect uncertainties from stellar mass errors, as well as cosmic variance, and counting statistics. The dashed symbols near each data point show how these values would change if just using photometric redshifts. For comparison we show the stellar mass densities for systems with  $10^{11} M_{\odot} < M_{*} < 10^{11.5} M_{\odot}$  from Glazebrook et al. (2004) plotted as solid blue boxes. Note that shifts of  $\pm 0.05$  in redshifts have been applied so that the data points and error bars do not overlap.

Field Infrared Survey (Conselice et al. 2007a) covering the DEEP2 fields (Davis et al. 2002, 2006) from Conselice et al. (2007b). Figure 1 also shows the number densities of galaxies within these mass ranges measured in the nearby universe to  $z \sim 0.2$  by the 2MASS/2dF galaxy surveys (Cole et al. 2001), normalized using the same Chabrier IMF used for the higher redshift stellar masses. The number density evolution of these massive galaxies demonstrates that statistically there is very little to no evolution at  $z < 1$  for the  $M_{*} > 10^{11} M_{\odot}$  systems. This appears to support the idea that massive galaxies are present by  $z \sim 1$  (e.g., Cimatti et al. 2006; Bundy et al. 2006; Brown et al. 2007).

However, as can be seen by eye in Figure 1, within the observational errors, there is some evolution in number densities for  $M_{*} > 10^{11} M_{\odot}$ , and perhaps  $M_{*} > 10^{11.5} M_{\odot}$  selected galaxies between  $z \sim 1 - 1.5$ . The evolution in the number and mass densities can be examined quantitatively in a number of ways. When considering evolution just within this sample from  $z = 1.5$  to  $z = 1$  there are significant increases at masses  $10^{11} M_{\odot} < M_{*} < 10^{11.5} M_{\odot}$ , both in terms of number and mass densities. This is also the case when considering evolution between  $z \sim 1.5$  and  $z \sim 2$ . However, galaxies with  $M_{*} > 10^{11.5} M_{\odot}$  show an increase in number densities between  $z = 1.5$  to  $z = 0.4$  of a factor of  $2.7^{+1.8}_{-1.7}$ . This is significant only at the  $< 2\sigma$  level, considering all uncertainties. In fact, all of this evolution occurs at  $z > 1$ . Furthermore, there is a factor of  $1.3^{+0.74}_{-0.53}$  increase in the mass density associated with  $M_{*} > 10^{11.5} M_{\odot}$  galaxies at the same redshift

range, although this is also at less than  $3\sigma$  significance. There is an increase of  $11.2^{+8.7}_{-4.9}$  in number densities, and a factor of  $5.5^{+4.3}_{-1.7}$  increase in mass densities for systems with  $M_* > 10^{11.5} M_\odot$  from  $z \sim 2$  to  $z \sim 1$ . This is also an insignificant increase, and it is impossible to rule out that massive galaxies with  $M_* > 10^{11.5} M_\odot$  are all in place at  $z < 2$ .

An analysis of Figure 1 shows that the number densities of systems with  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$  increases by a factor of  $2.2^{+0.57}_{-0.41}$  between  $z = 1.4$  and  $z = 0.4$ , a result significant at  $> 4\sigma$ . Just as for the most massive systems, this evolution occurs completely at  $z > 1$ . Similarly, there is a factor of  $2.1^{+0.6}_{-0.35}$  increase in the integrated mass density for systems with  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$  within the same redshift range, also at  $> 4\sigma$  confidence. After correcting for incompleteness there is a factor of  $14.5^{+4.1}_{-2.8}$  evolution in the number densities, and a factor of  $10.7^{+3.1}_{-2.0}$  in mass densities between  $z \sim 2$  and  $z \sim 1$  for galaxies with  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$  (Conselice et al. 2007b).

The observed evolution is such that the most massive systems with  $M_* > 10^{11} M_\odot$  increase in number and mass densities by factors  $> 2-3$  at a significance  $> 3\sigma$ . Taken as a whole, we calculate that the scenario whereby the stellar mass and number densities of massive galaxies does not evolve between  $z \sim 1.5$  to  $z \sim 0.4$  can be rejected at  $> 8\sigma$  confidence. Therefore it does not appear that high mass galaxy formation, with the possible exception of  $M_* > 10^{11.5} M_\odot$  systems, is complete by  $z \sim 1.4$ , yet it is largely completed by  $z \sim 1$ . Therefore, the redshift range  $z \sim 1 - 1.5$  is the final epoch for the build up of the majority of the mass in massive galaxies. However, there could easily be a factor of 2 or 3 evolution in the mass and number densities for massive galaxies at  $z < 1$ , and we would not be able to measure this based on the current uncertainties in the measurements of these quantities. The best way to approach this problem is to determine if massive galaxies have any ongoing evolution based on physical features, through structure and star formation.

## 2.1. Structures and Morphologies

Investigating the structures and morphologies of galaxies is becoming recognized as one of the most important methods for understanding galaxies (e.g., Conselice 2003; Cassata et al. 2005; Trujillo et al. 2006), and for tracing the merger history at higher redshifts (e.g., Conselice et al. 2003a; Bridge et al. 2007).

Early work showed that massive galaxies at  $z < 1$  are generally early-types or disks (Brinchmann & Ellis 2000; Bundy et al. 2005). The overlap of Palomar NIR imaging and Hubble ACS imaging in the Extended Groth Strip (Davis et al. 2006) allows us to study in detail  $> 500$  galaxies with stellar masses  $M_* > 10^{11} M_\odot$  at  $z < 1.4$ . For nearly all of these systems, their magnitudes are bright enough such that effects due to redshift do not affect the ability to classify these systems either by eye, or through quantitative methods (e.g., Conselice et al. 2000c; Windhorst et al. 2002; Papovich et al. 2005; Taylor-Mager et al. 2006; Conselice et al. 2007b).

Conselice et al. (2007b) find a significant amount of morphological diversity among the  $M_* > 10^{11} M_\odot$  galaxies (Figure 2). At  $z < 1$ , 69% of  $M_* > 10^{11} M_\odot$  systems are early-types (elliptical, S0, compact), while 10% are disks, and 18% are peculiars. This is perhaps a surprisingly high fraction of peculiars within a massive galaxy selected sample, and suggests that some of these systems are

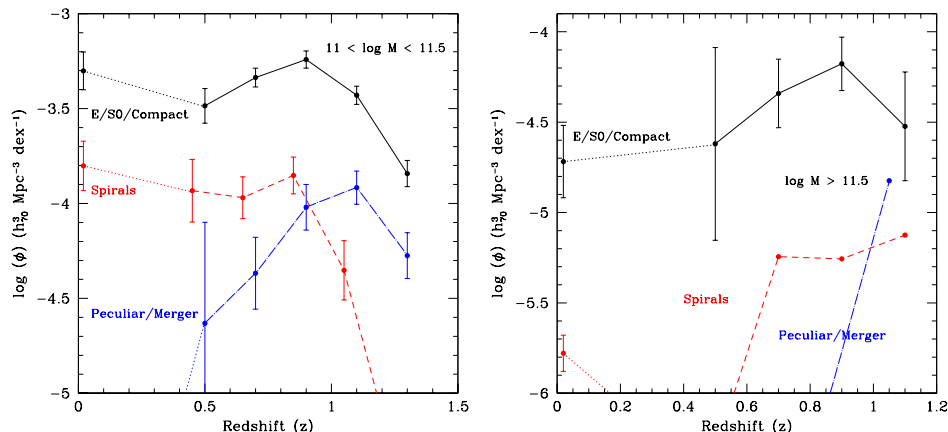


Figure 2. Visual estimates of the morphological evolution for massive galaxies with  $M_* > 10^{11} M_\odot$  taken from Conselice et al. (2007b) using ACS data. This figure is divided into two mass ranges, and shows the evolution of galaxy number densities at  $z < 1.4$ . The left panels shows the morphological breakdown up to  $z \sim 1.4$  for systems with  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$ . The right hand side shows the corresponding evolution for galaxies with  $M_* > 10^{11.5} M_\odot$ . The morphological fractions and densities for the  $z = 0$  systems are taken from Conselice (2006a).

still undergoing some type of mass assembly, possibly through merging or star formation. This changes slightly when examining only the most massive systems with  $M_* > 10^{11.5} M_\odot$ . These galaxies are  $\sim 90\%$  early-type over all redshifts, with a roughly similar number of mergers and disks making up the remainder. These results remain essentially the same, to within 5%, after considering how the Eddington bias may bring lower mass galaxies into our mass cuts due to observational uncertainty (see also Brinchmann & Ellis 2000; Bundy et al. 2005).

It is however clear that  $\sim 30\%$  of galaxies with  $M_* > 10^{11} M_\odot$  at  $z < 1.5$  are not early-types, which suggests that there is evolution in the massive galaxy population that cannot be seen simply through changes in number and mass densities. The disk galaxies show that there is some star formation occurring, and the peculiars reveal merger activity within this population.

Although early-types (classified E/S0/compact) dominate the massive galaxy population at both the  $M_* > 10^{11} M_\odot$  and  $M_* > 10^{11.5} M_\odot$  selection limits, these galaxies often contain evidence for morphological peculiarities. Usually these are in the form of outer low surface brightness features, or multiple cores. A total of 68 out of 263 ( $26 \pm 3\%$ ) ellipticals with  $M_* > 10^{11} M_\odot$  show some internal sub-structure visible by eye (Conselice et al. 2007b). These objects are perhaps seen in other ways, such as through color gradients and color structures in ellipticals (e.g., Menanteau et al. 2005; Stanford et al. 2004; Teplitz et al. 2006) resulting from star formation, and which may be related to these features. Previous studies have generally found that it is the lower mass ellipticals that contain these star formation signatures. These morphological disturbances however do not appear more common in the lower mass ellipticals, and in fact, 36% of the  $M_* >$

$10^{11.5} M_{\odot}$  ellipticals show this signature - a higher fraction than in the  $M_{*} > 10^{11} M_{\odot}$  population. These peculiarities are likely the result of recent merging activity in these systems within the past 1-2 Gyr before we observe them.

## 2.2. Star Forming Properties of Massive Galaxies

General Trends on the Color-Magnitude Diagram: A major question concerning high-mass galaxies is whether or not these systems have ongoing star formation at high redshift. While it is commonly thought that massive and early-type galaxies have largely finished their assembly and star formation by  $z \sim 1$ , detailed investigations suggest otherwise (e.g., Stanford et al. 2004; Teplitz et al. 2006; Conselice et al. 2007b).

One way to understand the star formation history of massive galaxies is to examine their position on color-magnitude diagrams. We show in Figure 3 the  $M_B$  vs.  $(U - B)_0$  diagram for  $M_{*} > 10^{11} M_{\odot}$  galaxies at  $z < 1.4$  taken from Conselice (2007b). Galaxies appear to separate into a red-sequence and a blue cloud in this parameter space (e.g., Strateva et al. 2001; Baldry et al. 2004; Bell et al. 2004; Faber et al. 2005). At the highest redshift bin shown,  $1.2 < z < 1.4$ , there is a significant number of massive galaxies that are not on the red-sequence. The fraction of massive galaxies on the red-sequence however increases at lower redshifts. This shows that massive systems with  $M_{*} > 10^{11.5} M_{\odot}$  generally fall in the red-sequence region at all redshifts, but with a significant number of systems in the blue cloud region at  $z > 0.8$ . The fraction of  $M_{*} > 10^{11} M_{\odot}$  galaxies on the red-sequence increases with time at all masses. Galaxies with lower masses show a similar pattern, yet lower mass galaxies always have a lower fraction of galaxies on the red-sequence at all redshifts, up to  $z \sim 1.4$ .

This leads to a very important conclusion regarding the red-sequence and high mass galaxies. Previous studies have examined the increase of the amount of stellar mass on the red-sequence, finding as much as a factor of two increase since  $z \sim 1$  (Bell et al. 2004; Faber et al. 2005; Brown et al. 2007). However, this increase is due to galaxies appearing on the red-sequence, which were previously blue, and not due to in-situ growth on the red-sequence itself. This can be clearly seen by massive galaxies gradually moving onto the red-sequence with time. This effect is also revealed in the decline in the number of blue massive galaxies found in the universe since  $z \sim 1$  (e.g., Bundy et al. 2006). This is not consistent with the idea that the red-sequence grows solely through the so-called ‘dry mergers’. Although merging may be present within the red-sequence, and within our massive galaxy sample, it does not appear to be the dominate method whereby the red-sequence grows.

Star Formation Rates: Quantifying star formation in massive galaxy samples can be done in several ways, including rest-frame UV emission, emission line fluxes, and Spitzer MIPS 24  $\mu\text{m}$  data. Perhaps surprisingly, about half of all massive galaxies at  $z \sim 1$  are detected at 24  $\mu\text{m}$ , after removing AGN contamination based on Chandra detections (Conselice et al. 2007b). After matching the MIPS and [OII] star formation indicators, Conselice et al. (2007b) find that  $\sim 40\%$  of the  $M_{*} > 10^{11} M_{\odot}$  systems at  $0.4 < z < 1.4$  are detected at 24  $\mu\text{m}$ . A total of  $37 \pm 5\%$  of the systems with  $M_{*} > 10^{11.5} M_{\odot}$  within this redshift range are detected at 24  $\mu\text{m}$ , with an average star formation rate of  $70 M_{\odot} \text{yr}^{-1}$ .

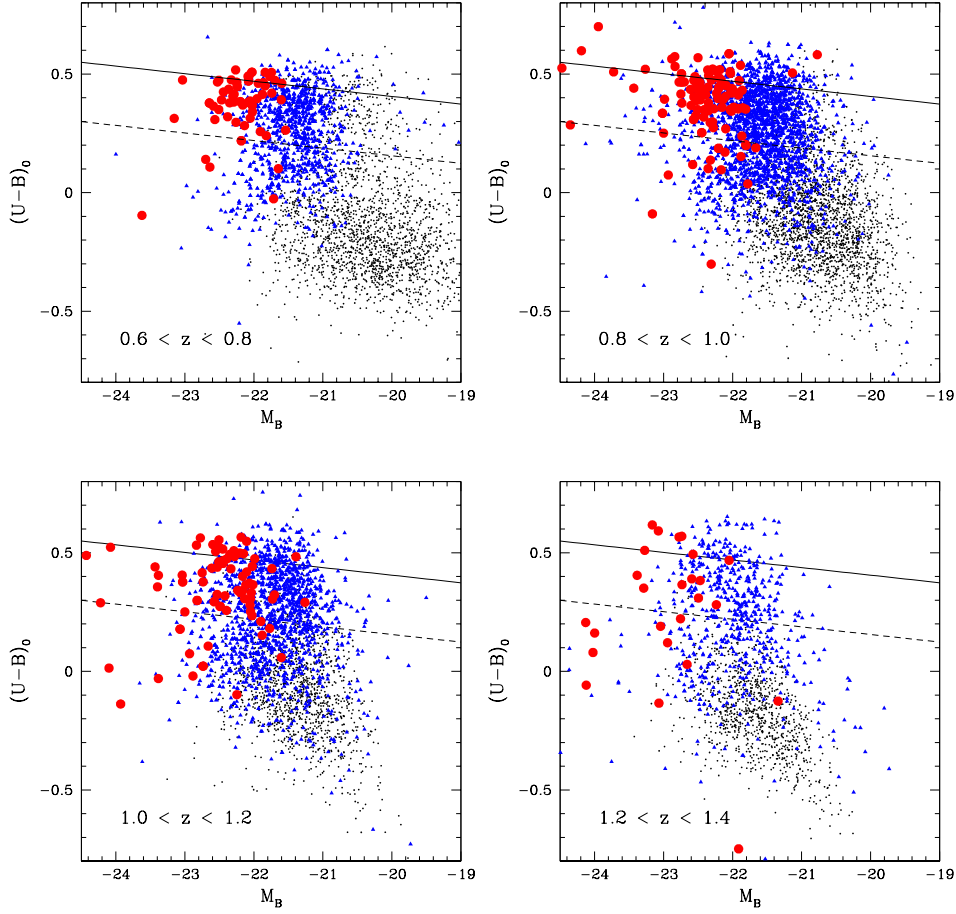


Figure 3. The  $(U - B)_0$  vs.  $M_B$  diagram for galaxies with  $M_* > 10^{10.5} M_\odot$  from  $z = 0.6$  to  $z = 1.4$ . The large red points on each panel are for galaxies with  $M_* > 10^{11.5} M_\odot$ . The blue triangles show the location of systems with  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$ . The solid line in each diagram shows the location of the red-sequence, as defined in Faber et al. (2005), and the dashed line is the demarcation between red and blue galaxies.

For galaxies with stellar masses  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$ , Conselice et al. (2007b) find that the fraction of galaxies undergoing star formation remains roughly similar at all redshifts. Circumstantially, this is consistent with the fact that the fraction of spirals+peculiar in this mass cut remains roughly constant throughout this redshift range. Interestingly, the fraction of systems which are undergoing star formation is higher than the non-elliptical fraction, showing that some morphologically classified massive ellipticals must be undergoing star formation (Stanford et al. 2004; Teplitz et al. 2006). The fraction of  $M_* > 10^{11.5} M_\odot$  galaxies with a significant  $24 \mu\text{m}$  detection declines slightly at lower redshift, from 33% at  $1.2 < z < 1.4$  to 14% at  $0.4 < z < 0.6$ , consistent with a drop in the morphological fraction of non-ellipticals. This is however certainly

a lower limit to the evolution, as the number of galaxies detectable at  $24\ \mu\text{m}$  declines at higher redshifts.

Conselice et al. (2007b) find, similar to previous studies utilising IR star formation indicators (e.g., Le Floc'h et al. 2005), a decline with redshift for the massive galaxy population. After fitting these star formation histories up to their plateau (i.e., at  $z \sim 1$ ) as a power-law  $\sim (1+z)^\alpha$  we can quantify the star formation history differences between  $M_* > 10^{11}\ M_\odot$  galaxies and  $M_* > 10^{11.5}\ M_\odot$  galaxies. For systems with  $M_* > 10^{11.5}\ M_\odot$ , Conselice et al. (2007b) find that the star formation rate declines as  $\alpha = 6 \pm 2.2$ , and for systems with  $10^{11}\ M_\odot < M_* < 10^{11.5}\ M_\odot$  the slope is fit as  $\alpha = 4.1 \pm 0.64$ . The overall decline in the entire galaxy population's star formation history can be parameterised as  $\alpha = 3 - 4$  (Hopkins 2004; Le Floc'h et al. 2005). It appears that while the  $10^{11}\ M_\odot < M_* < 10^{11.5}\ M_\odot$  galaxies have a similar decline as the overall field, the highest mass galaxies show a faster decline.

### 3. Galaxy Merging

A major question concerning massive galaxies is the role of mergers in their formation. Galaxy mergers are occurring in the universe, and it is likely that they play some role in the formation of massive galaxies, but the details are still debated. If mergers are occurring at  $z < 1$ , there are very few of them, and they might be nearly all dissipationless 'dry' mergers, without star formation. On the other hand, major mergers appear to be the dominate method for forming massive galaxies at  $z > 2$ .

CAS Structural Analysis and the Merger Rate: The CAS (concentration, asymmetry, clumpiness) parameters allow us to probe the structures of galaxies quantitatively, and are a major method for determining mergers in a galaxy population (e.g., Conselice et al. 2000a,b; Bershadsky et al. 2000; Conselice et al. 2004, 2005; Conselice 2003; Casatta et al. 2005; Bridge et al. 2007). The CAS system can also be used to identify relaxed massive ellipticals. The basic idea is that galaxies have light distributions that reveal their past and present formation modes (Conselice 2003). One benefit of using the CAS system for finding mergers is that it allows us to quantify the merger rate and the number of mergers occurring in a galaxy population (Conselice et al. 2003a; Conselice 2006b).

The location of massive galaxies with  $M_* > 10^{11}\ M_\odot$  at  $z < 1.4$  are generally found in CAS space at the locations where they are expected based on their visual morphologies. One important exception is that many of the visually classified non-distorted early-types are not located in the corresponding  $z \sim 0$  part of CAS diagrams, being slightly too asymmetric (Conselice et al. 2007b).

Using CAS values for massive galaxies with  $M_* > 10^{11}\ M_\odot$  Conselice et al. (2007b) determine the evolution of the non-dry merger fraction for massive galaxies (cf. Hernandez-Toledo et al. 2006 for understanding dry mergers within CAS). By using the the criteria, outlined in Conselice (2006b) of,

$$A > 0.35, A > S. \quad (1)$$

Conselice et al. (2007b) determined the merger fraction for the  $M_* > 10^{11}\ M_\odot$  galaxies out to  $z \sim 1.4$ . There is a slight decrease with redshift in the



merger fraction such that it declines as  $(1+z)^{1.3}$ , similar to the evolution seen in lower mass galaxies at  $z < 1$  (Conselice et al. 2003; Bridge et al. 2007).

Using the number densities of massive systems, and time-scales for CAS mergers, we can calculate the merger rate for  $M_* > 10^{11} M_\odot$  galaxies based on the merger fraction, and the time-scales for merging derived from N-body models. From this, a major merger time-scale of  $\tau = 0.43 \pm 0.05$  Gyrs for a galaxy with a mass of  $3 \times 10^{11} M_\odot$  is calculated (Conselice et al. 2007b).

The merger rate of massive galaxies at  $z < 1$  can then be calculated through the merger rate equation,

$$\mathcal{R}(z) = f_m(z) \cdot \tau_m^{-1} n_m(z) \quad (2)$$

where  $n_m(z)$  is the number densities of objects, and  $f_m(z)$  is the merger fraction<sup>1</sup>. We find that, statistically, the merger rate for these  $M_* > 10^{11} M_\odot$  galaxies is constant from  $z \sim 0.4 - 1.4$ , and is on average  $\log \langle \mathcal{R} \rangle (\text{Gyr}^{-1} \text{Gpc}^{-3}) = 4.3_{-0.7}^{+0.4}$ .

We can furthermore calculate the total number of major mergers a galaxy with  $M_* > 10^{11} M_\odot$  undergoes from  $z \sim 1.4$  to  $z \sim 0.4$  using equation (11) in Conselice (2006b). We calculate that the average number of mergers a massive galaxy with  $M_* > 10^{11} M_\odot$  undergoes from  $z \sim 1.4$  to  $0.4$  is  $N_m = 0.9_{-0.5}^{+0.7}$ . Thus, on average, a massive galaxy will experience about one major merger from  $z \sim 1.4$  to  $0.4$ , roughly consistent with other results (Conselice 2006b; Bell et al. 2006).

Dry-Merging at  $z < 1$ : One issue which is not clear is how much of the merger and star formation process, and especially the controversial and hard to find dry mergers, are responsible for the addition of mass in massive galaxies at  $z < 1$ . We can address this using mass functions, and the measured star forming histories of galaxies with  $M_* > 10^{11} M_\odot$  and  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$ . While the star formation history matches the increase of the stellar mass, within massive galaxies, to within  $< 3 \sigma$  at any one redshift, the fact that the star formation history is consistently lower implies that star formation statistically cannot account for the total increase in stellar mass. This implies that part of the mass growth in these systems must be accounted for by mergers, or galaxies with masses lower than each stellar mass limit evolving into the higher mass bin due to star formation and/or merging.

Between the bins  $M_* > 10^{11.5} M_\odot$  and  $10^{11} M_\odot < M_* < 10^{11.5} M_\odot$  the amount of stellar mass added to the higher mass bin can be measured partially through the star formation rate. The star formation rate within a bin will increase the amount of mass within that bin, and star formation in a lower mass bin will increase the mass and number densities in higher mass bins by bringing up galaxies. When comparing the changes in the mass function to the amount of new mass from star formation, it is clear that changes in mass and number densities cannot be totally accounted for by just star formation. The remainder of the excess must be produced through merging. In Conselice et al. (2007b) it is argued that the amount of merging is such that at least one major merger

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<sup>1</sup>Note that this is not the galaxy merger fraction, which is the fraction of galaxies merging, which is roughly double the merger fraction (Conselice 2006b).

is occurring for  $M_* > 10^{11.5} M_\odot$  galaxies at  $z < 1.5$ . Since these galaxies are largely early-types, it is likely that many of these mergers are dry (see also Bell et al. 2005). This roughly agrees with the number of mergers calculated through the CAS parameters.

High-redshift  $z > 2$  mergers: The situation at higher redshifts however appears to be different, and it is likely that the majority of the stellar mass in modern ellipticals was put into place through major mergers at  $z > 1.5$ . Massive galaxies at  $z > 2$  are not smooth ellipticals, but appear peculiar, even in the rest-frame optical (Conselice et al. 2005). In fact, the CAS values for these galaxies reveals a merger fraction of roughly 40-50% (Conselice et al. 2003).

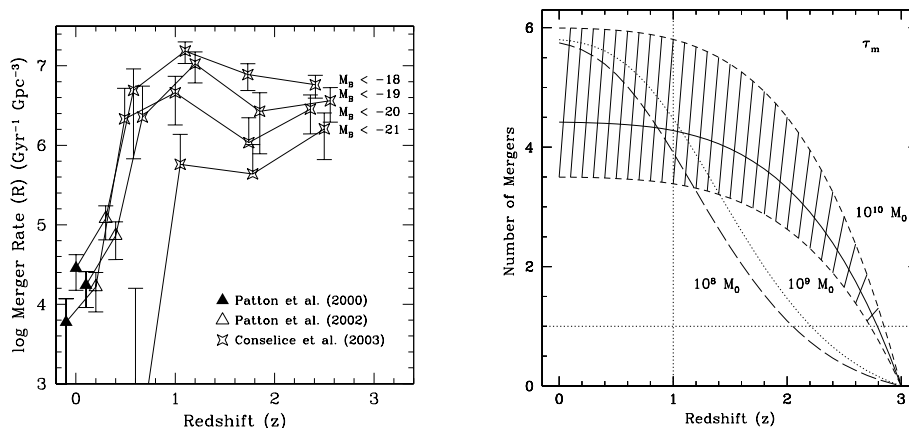


Figure 4. Evolution of the merger rate, in units of Gyr and co-moving  $\text{Gpc}^3$ , as a function of redshift and observed magnitude (left panel), and the empirically determined integrated number of major mergers since  $z \sim 3$ . These merger rates and histories are taken from previously published merger fractions (see Conselice 2006b and references therein.)

By integrating the merger rate since  $z \sim 3$  Conselice (2006b) finds that a typical massive galaxy with  $M_* > 10^{10} M_\odot$  undergoes  $4.4^{+1.6}_{-0.9}$  mergers from  $z = 3$  to  $z = 0$  (Figure 4). Most of these mergers are at  $z > 1.5$ . An additional feature of the N-body models analyzed in Conselice (2006b) is the ability to determine the merging galaxy mass ratios that can produce high asymmetries. The result of this is that the CAS method is only sensitive to major mergers, that is mergers with a mass ratio of 1:3 or lower (see also Hernandez-Toledo et al. 2005). This also allows us to determine how much mass is likely added to galaxies due to the merger process since  $z \sim 3$ . The result is that a galaxy which undergoes on average 4 - 5 major mergers will increase its total mass by a factor of  $\sim 10$ . This is consistent with direct observations which show that the most massive galaxies are generally in place by  $z \sim 1.5 - 2$ , but are significantly depleted in number at  $z > 2$  (Fontana et al. 2004).

#### 4. Discussion and Summary

The last few years have seen a number of studies designed to determine when massive galaxies in the universe formed. These studies have generally concluded that massive galaxies in the universe, typically those with  $M_* > 10^{11} M_\odot$ , are largely formed by  $z \sim 1$ , but with considerable uncertainty. This is statistically found to be the case in nearly all studies in terms of mass and number densities, for systems with  $M_* > 10^{11} M_\odot$  from  $z \sim 1$ , although there is measurable evolution from  $z \sim 1.4$  (Conselice et al. 2007b).

While studies have found that the number and mass densities of massive galaxies are similar at  $z < 1$ , this does not necessarily imply that there is no evolution in this population. Using results from the wide and deep Palomar Observatory Wide-Field Infrared Survey, combined with DEEP2 spectroscopy, we can directly select and study the properties and evolution of  $M_* > 10^{11} M_\odot$  galaxies at  $0.4 < z < 1.4$ . Based on the findings of this survey (Bundy et al. 2006; Conselice et al. 2007b) it appears that the stellar mass and number densities of  $M_* > 10^{11} M_\odot$  galaxies does not change significantly at  $z < 1$ . We however cannot rule out factors of 2-3 in number and mass density evolution for these systems, based solely on densities, due to the uncertainties in these measurements.

Other methods besides densities, are therefore need to conclusively argue whether massive galaxies are finished forming by  $z \sim 1$ . The fact that a high fraction of massive galaxies are forming stars (40%), and are non-elliptical (30%), at  $z \sim 1$  suggests that there is active evolution. We find that in addition to star formation activity, a typical massive galaxies with  $M_* > 10^{11} M_\odot$  will undergo, on average, a single merger at  $z < 1.4$ . Most of the formation for these massive galaxies occurs at higher redshifts. Observationally, there is a significant decrease in the number densities of massive galaxies at  $z > 2$ . These systems are also observed to be undergoing a significant amount of merging which is likely how they build up most of their mass by  $z \sim 2$ .

Furthermore, these results show that the study of ‘early-types’, defined through luminosity, color, morphology or stellar mass, at high redshift must be carefully done, and results of studies will vary significantly, depending on selection. It is clear, particularly at high redshift, that red galaxies are not the equivalent of massive galaxies, or elliptical galaxies, and each of these populations must be studied individually.

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